Analysis of the NPOESS VIIRS Land Surface Temperature Algorithm Using MODIS Data

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***Abstract*—The Visible Infrared Imaging Radiometer Suite (VIIRS) will replace the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) and the National Aeronautics and Space Administration's (NASA) Moderate Resolution Imaging Spectrometer (MODIS) as the nation's wide-swath multispectral sensor following the launch of the National Polar Orbiting Environmental Sensor Suite (NPOESS) Preparatory Project (NPP) in about 2008. Through the follow-on NPOESS program, VIIRS data will be the primary source of systematic land remote sensing products until about 2022. Together, the AVHRR/MODIS/VIIRS satellite series will provide a critical long-term data record for Earth studies. In the NPP/NPOESS program, the product algorithms and production environments are developed and managed by private industry. This is a significant change from the current NOAA and NASA programs, and NPOESS algorithm deviations from successful heritage approaches (e.g., Earth Observation System) warrant comprehensive independent testing. The current baseline VIIRS land surface temperature (LST) algorithm represents one such deviation. In the present study, we evaluated the VIIRS LST by adapting it for use with 60 scenes of MODIS Level 1b radiance data. Algorithm coefficients were derived from MODTRAN4 radiative transfer model simulations. Using the validated MODIS LST (MYD11_L2) product as a reference, we found that precision errors in the VIIRS dual split window (DSW) algorithm (the current "main" approach) significantly exceed those of the VIIRS split window (SW) algorithm (the current "backup" approach) in both daytime and nighttime conditions. Performance of both is better for nighttime cases than for daytime cases with all surface types. We attribute the larger errors in the DSW approach to its use of short middle infrared wavelengths which, compared to thermal infrared wavelengths, exhibit greater variability in surface emissivity and susceptibility to solar contamination. We conclude that a traditional SW algorithm, such as the current VIIRS backup algorithm, would provide superior performance to the DSW approach. An SW approach would also provide more seamless continuity with heritage products. Although this is not an NPOESS requirement, it is a key objective for multimission climate data records and Earth system data records.**

***Index Terms*—Land surface temperature (LST), Moderate Resolution Imaging Spectrometer (MODIS), National Polar Orbiting Environmental Sensor Suite (NPOESS), NPOESS Preparatory Project (NPP), split window (SW), Visible Infrared Imager Radiometer Sensor (VIIRS).**

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I. Introduction

LAND surface temperature (LST) is a key proxy of Earth surface energy and is used in a range of hydrological, meteorological, and climatological applications (e.g., [1]). The National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS) underscored the importance of a long-term global LST record by including this variable in its "24 EOS Measurements" [2].

The moderate-resolution LST time-series originated, and continues to present, with the Advanced Very High Resolution Radiometer (AVHRR) brightness temperature record from the National Oceanic and Atmospheric Administration's (NOAA) polar orbiting satellites (1982 to present; [3], [4]). In 2000, NASA initiated an atmospherically corrected LST record based on Moderate Resolution Imaging Spectrometer (MODIS) data [5]. Beginning in about 2008, these series will be continued by data from the Visible Infrared Imager Radiometer Sensor (VIIRS) sensor onboard the National Polar Orbiting Environmental Sensor Suite (NPOESS), and the "bridge" satellite linking the EOS and NPOESS programs: the NPOESS Preparatory Project (NPP) [6].

The NPP/NPOESS program represents a major transition in the development and production of LST and other geophysical products from U.S. environmental satellites. In the NPP/NPOESS era, the satellites, algorithms, and production facilities are developed and operated in the commercial sector to meet performance criteria that were bid to the government in a competitive proposal. Additionally, the government has formed algorithm teams composed of science community experts to support the program through technical interchange. It is within the latter context that we evaluate the VIIRS LST algorithms in the present study.

Multiple LST algorithms have been developed and applied to satellite data. Physics-based approaches include the two-temperature method [7], the temperature emissivity separation method [8], [9], and the day/night method [10]. Physics-based algorithms typically require samples from middle and thermal infrared (TIR) spectral bands or multiple orbits. For example, the MODIS Land Team currently uses the day/night method to produce a Level 3 gridded LST product. The day/night algorithm dynamically estimates both emissivity and LST, since these parameters vary differently in time and space. However, to execute successfully, the algorithm requires non-cloudy observations in a consecutive day and night pair. This limits its applicability.

To simplify processing and data needs, most LST algorithms use the split window (SW) [3] approach, a technique adapted from sea surface temperature (SST) algorithms. The SW method corrects for atmospheric effects in TIR bands by exploiting the differential absorption of atmospheric water vapor between adjacent bands [3], [11]–[14]. The basic functional form of SW methods is a first-order Taylor series expansion of Planck's equation—a method both rapid and robust in operation. Most published SW equations, including the MODIS Level 2 swath algorithm [14], also attempt to compensate for surface emissivity through the use of ancillary information (e.g., land cover maps). The resulting formulae estimate the surface kinetic temperature, sometimes called the "skin" temperature.

The current VIIRS LST main algorithm, which is developed and tested by private industry using model data [15], is a major variant of traditional SW approaches. Specifically, the algorithm employs a "dual split window" (DSW) approach that depends on two middle infrared and two thermal infrared bands. Different DSW algorithmic forms are used for day and night; however, neither has an operational heritage. To our knowledge, this was the first application of DSW approach to LST. Further, VIIRS currently retains a new SW algorithm as a backup algorithm [15]. According to the VIIRS system specification [16], these algorithms must achieve a precision error (standard deviation) of ≤ 0.5 K, an accuracy (mean bias) error of ≤ 2.4 K, and an uncertainty (root mean square) error of ≤ 2.5 K. In this terminology, uncertainty is equivalent to the square root of the sum of the squares of the accuracy and precision values achieved in operation.

The VIIRS LST algorithms have been tested with model data [17]. However, the new LST approaches have not been tested extensively with real satellite data. Real data are critical since models unavoidably have biases, and since the Earth's complex natural variability cannot be fully simulated. The MODIS Land Discipline Team, for instance, found that simulated data had limited use in exposing shortcomings in its algorithms (E. Vermote, personal communication, 2003).

In the present study, we conducted a prelaunch evaluation of the VIIRS LST by adapting its algorithms to work with MODIS Level 1b top-of-atmosphere (TOA) radiance data. We sought to determine the following:

- characteristics of the VIIRS DSW algorithm, such as its vulnerability to solar contamination, water vapor, and natural variability in surface emissivity;
- how the current VIIRS LST products compare to the validated MODIS LST products [5] for daytime and nighttime scenes ($\sim$ 2330 km $\times$ 2340 km each) and different surface types;
- if the current VIIRS main and backup algorithms are sufficiently consistent that they could be applied seamlessly within a scene;
- if the VIIRS LST algorithm is well suited for climate data records (CDRs) [28] and Earth system data records (ESDRs).

The outline of this paper is as follows. In Section II, we provide details of the VIIRS sensor and LST algorithms. In Section III, we describe our adaptation of the VIIRS LST algorithms to work with MODIS data and our approach to evaluating algorithm performance. Section IV gives quantitative comparisons of the VIIRS LST and the operational MODIS LST products. We conclude this paper with a discussion and conclusions in Sections V and VI, respectively.

II. VIIRS Sensor Algorithms

A. Sensor Design

VIIRS has 22 spectral bands, including 16 moderate-resolution (750-m pixels) and five imagery resolution (375-m pixels) bands, plus one panchromatic "Day-Night Band" [6], [16]. The central wavelengths of the VIIRS thermal infrared bands (10.8 and 12.0 μm), used in LST retrievals, are similar to those of MODIS (11.0 and 12.0 μm) and AVHRR (10.8 and 12.0 μm). VIIRS features a rotating telescope design to minimize stray light, and includes onboard calibration sources for solar and thermal bands.

VIIRS will be onboard the NPP satellite (altitude 824 km; Sun-synchronous orbit with 1030 local equator crossing time) and three simultaneous NPOESS satellites (altitude 833 km; Sun-synchronous orbits with 0530, 0930, and 1330 local equator crossing times). Given the sensor's $\pm 56^\circ$ field of view, these orbits provide a swath width of $\sim$3000 km. Pixel growth with scan angle is constrained; however, measurement signal-to-noise values decrease (discontinuously) toward swath edges. LST will be processed over the full swath; however, it need only meet the accuracy, precision, and uncertainty specifications over the 2000-km central subsection [16]. The nadir horizontal cell size will be 750 m.

VI. Concluding Remarks

Our results strongly suggest that the VIIRS SW LST algorithm is superior to the VIIRS DSW LST algorithm both for daytime and nighttime conditions. Specifically, differences between the VIIRS SW LST and the validated MODIS LST had lower variances than did those of the DSW algorithm. Thus, the SW algorithm leads to smaller precision and uncertainty errors (where uncertainty is the root sum of squares of accuracy and precision errors). Precision errors and uncertainty for both VIIRS algorithms were greater in the daytime compared to the nighttime. The consistency of the differences over the 60 MODIS 5-min scenes suggests that the VIIRS LST algorithms are stable in daytime and nighttime.

Our results also suggest the current VIIRS algorithm will provide inconsistent results in scenes with sun glint areas ($< 20^\circ$ from specular reflectance angle), where solar contamination in short-middle infrared measurements can be significant. In our tests, sun glint pixels occurred in up to 25% of all pixels in a daytime scene. In the current VIIRS LST algorithm design, the backup SW algorithm is used over sun glint areas. The required algorithm "switching" (from DSW to SW and back) for this within such scenes undoubtedly will introduce variability in spatial error characteristics—an undesirable artifact of the current design. The VIIRS DSW approach is also inconsistent with heritage algorithms used with AVHRR, MODIS, and GOES. Although not an NPOESS program requirement, these inconsistencies will challenge efforts to build seamless multimission data records per NASA's and NOAA's goals [28].

Given the likely longevity of the NPOESS data record, we conclude that the currently planned use of dual SW algorithms is thus far not justified. Barring further algorithm development (e.g., increased stratification of surface types, dynamic emissivity estimation, or better global surface type maps), we suggest that the VIIRS LST algorithm design be reconsidered.